

How rapidly do neutron stars spin at birth?

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ABSTRACT

We have studied the X-ray properties of ageing historical core-collapse supernovae in nearby galaxies, using archival data from *Chandra*, *XMM-Newton* and *Swift*. We found possible evidence of a young X-ray pulsar in SN 1968D and in few other sources, but none more luminous than \sim a few 10^{37} erg s^{−1}. We compared the observational limits to the X-ray pulsar luminosity distribution with the results of Monte Carlo simulations for a range of birth parameters. We conclude that a pulsar population dominated by periods \lesssim 40 ms at birth is ruled out by the data.

Key words: supernova remnants, pulsars: general

1 X-RAY SUPERNOVAE AND PULSARS

X-ray imaging missions have detected \approx 40 young core-collapse supernovae (SNe); this has led to a deeper understanding of the initial phases of shock expansion. However, only \approx 10 SNe have been detected in the X-ray band at ages $>$ 20 yr, even though there is a reliable optical record of historical SNe in nearby galaxies over \approx 100 yrs. On the other hand, core-collapse SN remnants are found with much older ages (\gtrsim 350 yrs). But we still know little about the shock propagation into the ambient medium during the transition between the SN and SN remnant phases (ages of \sim 30–300 yrs). Thus, it is important to search for and study historical SNe as far as possible into this age range.

From the X-ray point of view, the main phases of SN evolution are (Fransson et al. 1996):

a) *SN phase = circumstellar medium interaction*: the shock propagates into the stellar wind of the progenitor star. Emission from the forward shock (gas temperature \gtrsim a few keV) dominates only in the very early epoch ($t \lesssim$ 100 d); then, after the shell of ejecta becomes optically thin, the reverse shock provides the X-ray photons (thermal spectrum at $kT \approx$ 0.5–1 keV). The older the SN, the further back in time we probe the mass-loss rate of the progenitor star, and hence its evolution in the last few thousand years.

b) *SN Remnant phase = interstellar medium interaction*: the expanding shock reaches the boundary between the stellar wind bubble and the surrounding interstellar medium. When that happens, the luminosity decay flattens out, and the remnant may keep a constant or very slowly declining luminosity and temperature for \sim a few 10^3 yrs.

This scenario can have an additional component. A large fraction of core-collapse SNe will leave behind a spinning, isolated neutron star (NS) powered by electromagnetic

losses. For a dipole magnetic field B , the energy loss is given by (assuming an orthogonal rotator) $\dot{E}_{\text{rot}} = B^2 \Omega^4 R^6 / 6c^3$, where R is the NS radius and Ω its angular velocity. There is an empirical relation (Possenti 2002) between the X-ray luminosity of the pulsar and its rotational energy loss: $\log L_{\text{X},[2-10]} = 1.34 \log \dot{E}_{\text{rot}} - 15.34$. Analogous relations were inferred by Li et al. (2008) and Kargaltsev & Pavlov (2008). The X-ray luminosity includes both the magnetospheric emission from the pulsar itself, and the synchrotron emission from the pulsar wind nebula. It has a power-law spectrum with photon index $\Gamma \approx 2$. It declines as $L_{\text{X}} = L_{\text{X},0}(1 + t/t_0)^{-2}$, where $t_0 \sim$ a few 10^3 yrs. For $t \lesssim t_0$ the pulsar flux does not vary significantly. Therefore, for some SNe with very energetic pulsars (e.g., the Crab), the hard X-ray emission from the pulsar itself becomes progressively more important than the thermal emission from shocked gas, as the SN ages. In external galaxies, X-ray imaging cannot resolve the shocked gas from the point-like pulsar, but X-ray spectra and colors can tell which component dominates.

The pulsar luminosity distribution is determined by the magnetic field and initial spin period distributions. The magnetic field distribution is relatively well constrained ($\sim 10^{12}$ – 10^{13} Gauss). Instead, the birth spin is very uncertain. Some radio studies have suggested a large population of millisecond pulsars (Arzoumanian et al. 2002), while others have claimed millisecond pulsars are very rare (Faucher-Giguere & Kaspi 2006). We have recently proposed a new, independent method to constrain the initial period distribution of pulsars and solve this controversy (Perna et al. 2008). Using *Chandra*, *Swift* and *XMM-Newton* data, we have compared the observed X-ray luminosities (or upper limits) of young SNe with the predicted distribution of pulsar X-ray luminosities.

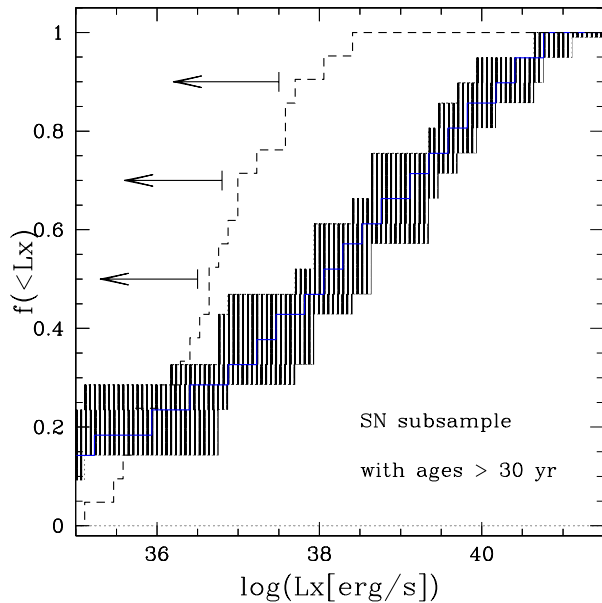


Figure 1. The dashed line shows the distribution of 2–10 keV luminosities (measurements or upper limits) for historical SNe with ages > 30 yrs; they are treated as upper limits for the underlying pulsar luminosities. The solid line (with shaded 1σ error) shows the predicted pulsar luminosity distribution.

2 THE OLDEST X-RAY SUPERNOVAE

A spin-off of our observational study (Soria & Perna 2008) was the discovery or recovery of three pre-1970 X-ray SNe, that is in the characteristic age range when the outgoing shock reaches the interstellar medium. The oldest X-ray SN we have discovered is SN 1941C, with $L_X \approx 5 \times 10^{37} \text{ erg s}^{-1}$ in the 0.3–10 keV band (Table 1). For SN 1959D, we infer $L_X \sim \text{a few } 10^{37} \text{ erg s}^{-1}$. For SN 1968D, the emitted luminosity $L_X \approx 2 \times 10^{38} \text{ erg s}^{-1}$, mostly thermal (i.e., from the shocked gas), but with an additional power-law component with photon index ≈ 2 and $L_X \approx 2 \times 10^{37} \text{ erg s}^{-1}$. In total, there are only 27 historical core-collapse SNe from 1900–1970, at distances $\lesssim 15 \text{ Mpc}$ (for many other old SNe, the type is undetermined). Of them, 17 are so far undetected in X-rays, down to $\sim \text{a few } 10^{37} \text{ erg s}^{-1}$; 4 are detected at similar luminosities; the remaining 6 have not yet been observed by *Chandra* or *XMM-Newton* (apart from snapshots, too short to provide meaningful constraints).

For our fitted luminosity of SN 1941C, we infer a mass-loss rate from the progenitor star $\approx 5 \times 10^{-5} M_\odot \text{ yr}^{-1}$ at $\approx 55,000 \text{ yr}$ before the SN (Soria & Perna 2008). For SN 1968D, the inferred mass-loss rate is $\approx 8 \times 10^{-5} M_\odot \text{ yr}^{-1}$ at $\approx 30,000 \text{ yr}$ before the SN. The X-ray luminosity and mass-loss rate of SN 1968D suggest that this SN is evolving to a remnant similar to Cas A. The similarity between SN 1968D and Cas A was also noted from radio observations (Hyman et al. 1995). The radio behaviour of SN 1968D was also found to be similar to that of another SN in NGC 6946, 1980K (Hyman et al. 1995), which we have recovered in the *Chandra* observations from 2002–2004, at a luminosity $\approx 4 \times 10^{37} \text{ erg s}^{-1}$, in the 0.3–8 keV band (Soria & Perna 2008). The presence of a power-law-like emission component above 2 keV in SN 1968D suggests that there may be

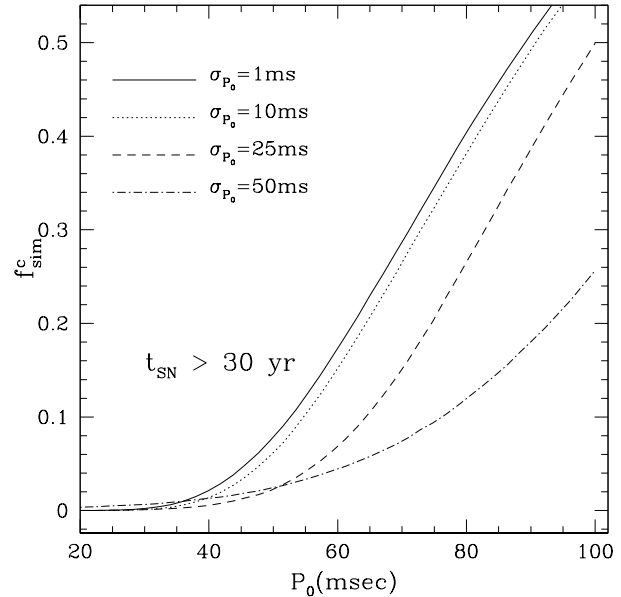


Figure 2. Fraction f_{sim}^c of Monte Carlo realizations of the SN sample for which the predicted pulsar luminosities are consistent with the observed limits of the corresponding SNe. This is shown for different distributions of the initial spin periods, described by Gaussians of mean P_0 and dispersion σ_{P_0} . This sample includes only SNe older than 30 yrs.

a contribution from a young pulsar and its wind nebula; its luminosity $\approx 10^{37} \text{ erg s}^{-1}$ is comparable to the luminosity of Crab-like systems (Possenti 2002), and in particular the Crab itself and PSR B0540–69 (Serafimovic et al. 2004).

3 CONSTRAINTS ON BIRTH PARAMETERS

We started from the results of a recent large-scale radio pulsar survey (Arzoumanian et al. 2002): for a dipole approximation, the magnetic field has a log-normal distribution with a mean value $\log B_0(\text{Gauss}) = 12.35$, $\sigma_{B_0} = 0.4$; the initial birth period distribution has a mean $\log P_0(\text{s}) = -2.3$, $\sigma_{P_0} > 0.2$. In order to test the resulting theoretical predictions for the pulsar distribution of X-ray luminosities, we performed Monte Carlo realizations of the compact object remnant population. The fraction of SNe that leave behind a NS has been theoretically estimated by Heger et al. (2003) as $\approx 87\%$ (subject to variability depending on stellar metallicity and initial mass function). If an object is a BH, we assigned it a luminosity $< 10^{35} \text{ erg s}^{-1}$. For the NSs, the birth period and magnetic field in our simulation were drawn from the Arzoumanian distribution, and were evolved to the current age. The corresponding X-ray luminosity was then drawn from a log-Gaussian distribution derived from the Possenti relation. When comparing the predicted and observed X-ray luminosity distributions, we need to consider the possibility of obscuration. However, we suggest (see discussion in Perna et al. 2008) that neutral absorption does not strongly affect our results, particularly in the 2–10 keV band, because we considered only SNe older than 30 years (an analysis of all those older than 10 years gives the same statistical result); also, luminous X-ray pulsars would ionize

Table 1. Unambiguously-identified core-collapse SNe in nearby galaxies ($d \leq 15$ Mpc) until 1970, and luminosity or upper limits to the *power-law component* of their X-ray emission (upper limit to the luminosity of a possible young pulsar). All values derived from *Chandra* data, except where noted.

SN ID	Type	Galaxy	Distance (Mpc)	$L_{\text{po},0.3-8}$ (erg s $^{-1}$)	Notes
1909A	II	M101	7.4	$< 5 \times 10^{36}$	
1917A	II	N6946	5.5	$< 2 \times 10^{36}$	
1921B	II	N3184	8.7	$< 10^{37}$	
1923A	IIP	M83	4.5	$< 3 \times 10^{36}$	
1937A	IIP	N4157	15	$< 3 \times 10^{37}$	(a)
1937F	IIP	N3184	8.7	$< 10^{37}$	
1940A	IIIL	N5907	13	$< 2 \times 10^{37}$	(a)
1940B	IIP	N4725	13	$< 3 \times 10^{37}$	
1941A	IIIL	N4559	10	$< 2 \times 10^{37}$	
1941C	II	N4136	10	5×10^{37}	(b)
1948B	IIP	N6946	5.5	$< 2 \times 10^{36}$	
1951H	II	M101	7.4	$< 5 \times 10^{36}$	
1954A	Ib	N4214	3.0	$< 5 \times 10^{35}$	
1959D	IIIL	N7331	15	$\sim \text{a few } 10^{37}$	(b)
1961U	II	N3938	12	?	
1961V	IIIn	N1058	9.1	$< 3 \times 10^{37}$	
1962L	Ic	N1073	15	$< 2 \times 10^{38}$	
1962M	IIP	N1313	4.0	$< 2 \times 10^{36}$	
1964H	II	N7292	15	?	
1964L	II	N3938	12	?	
1966J	Ib	N3198	12	?	
1968D	II	N6946	5.5	2×10^{37}	(b)
1968L	IIP	M83	4.5	$< 3 \times 10^{36}$	
1969B	IIP	N3556	14	$< 3 \times 10^{37}$	
1969L	IIP	N1058	9.1	$< 3 \times 10^{37}$	
1970A	II	IC3476	10	?	
1970G	IIIL	M101	7.4	$\approx 10^{37}$	(c)

NOTES – (a) From *XMM-Newton* data; (b) Soria & Perna (2008); (c) Immler & Kuntz (2005).

the entire mass of the ejecta on a time-scale between a few years and a few tens of years.

We find (Fig. 1) that out of the 106 Monte Carlo realizations of the sample, none of them predicts pulsar luminosities compatible with the observed SN X-ray limits. The predicted high-luminosity pulsars, corresponding to those with the shortest initial periods, are not observed. This suggests that the mean initial period of the pulsar population is slower than the millisecond periods derived from some population-synthesis studies in the radio (Arzoumanian et al. 2002). A number of other recent investigations have reached similar conclusions. For example, the population-synthesis studies of Faucher-Giguere & Kaspi (2006) yielded a good fit to the data with a mean birth period of 0.3 s, $\sigma = 0.15$ s, for $\log B_0(\text{Gauss}) = 12.35$. Similarly, the analysis by Ferrario & Wickramasinghe (2006) yielded a mean period of 0.23 s for a magnetic field of 10^{12} Gauss. We performed Monte Carlo simulations of the X-ray pulsar population using those birth parameters and found them to be consistent

with our SNe X-ray limits. We obtain a quantitative limit on the birth period by plotting (Fig. 2) the fraction of Monte Carlo simulations for which the luminosity of each pulsar is found below that of the corresponding SN (that is, the fraction of “acceptable” configurations), for different values of standard deviations. Mean periods shorter than ≈ 40 ms are ruled out at the 90% confidence limit, for any assumed value of the width of the period distribution (Perna et al. 2008). This is also consistent with studies of young Galactic SNRs (Srinivasan et al. 1984).

A possible reason for the lack of luminous X-ray pulsars is a turnover in the efficiency of conversion of rotational energy into X-ray luminosity (relation between \dot{E}_{dot} and L_X), at high values of \dot{E}_{dot} . Another systematic effect that might affect our results is that a fraction of NSs may be born with a non-active magnetosphere. Similarly, the precise fraction of BHs versus NSs in the remnant population plays a role in our results. A larger fraction of BHs would alleviate our constraints on the initial spin periods, while a smaller fraction would make them tighter. Our results for the bulk of the pulsar population do not exclude that the subpopulation of magnetars could be born with very fast spins. But their spin-down times would be very short, and the spin-down X-ray luminosity would decline within the first few months, during which the SN is still too optically thick to let the pulsar X-ray photons go through. Therefore, our analysis cannot place meaningful constraints on this class of objects.

Finally, our results have implications on the contribution of young X-ray pulsars to the population of ultraluminous X-ray sources observed in nearby galaxies. Earlier models predicted that a sizable fraction of that population could be made up of young, fast-rotating pulsars (Perna & Stella 2004). However, our study shows that the contribution from this component, although expected from the tail of the population, cannot be significant.

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